Status and Trends in the Southern California Spiny Lobster Fishery and Population: 1980–2011

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Abstract.—The California spiny lobster (*Panulirus interruptus*) fishery in southern California ranks amongst the State's most economically important fisheries. An analysis of commercial harvest data confirms that the fishery was landing near-record catches in the late-2000s through early-2010s. Advances in recreational fishing technology likely tempered commercial fishery landings per unit effort. The commercial catch per trap pulled declined 15%, on average, in years after the introduction of a new rigid-style hoop net in the recreational fishery. Fishery-independent data sourced from power plant marine life monitoring recorded increased California spiny lobster abundance after 1989 with evidence of increased larval settlement beginning circa 1989. This timing was consistent with previously reported oceanographic changes in the North Pacific. Abundance indices for lobsters likely one-year's growth away from recruiting into the fishery and the young-of-the-year, both derived from power plant abundance records, significantly predicted the commercial landings at index-appropriate temporal lags, i.e. one year for next year's recruitment. Carapace lengths measured during power plant surveys in Santa Monica Bay, where commercial fishing was prohibited, significantly declined for the total sample and females only after the introduction of the new rigid hoop net. Male carapace lengths were not significantly different between the two periods. The power plant data confirms that, as of 2012, the fishery appears healthy but warns of the need to monitor sublegal individuals and their dependence on oceanographic conditions. These analyses also indicate the urgency of monitoring the recreational fishery harvest, especially the potential effects of the new rigid hoop net.

Exploitation of spiny lobsters (Family Palinuridae) occurs worldwide. These fisheries rank among the most economically valuable in their respective regions (Phillips 2006; Lipcius and Eggleston 2008). Historically, substantial research was directed at understanding spiny lobster population variability (Polovina et al., 1995; Lipcius and Eggleston 2008) and predicting future fishery success by examining abundance indices of pre-recruitment size classes (Cruz et al., 1995; Cruz and Adriano 2001). These data commonly resulted in stock assessments and fishery management plans designed to maintain sustainable fisheries (Phillips et al., 2010). Despite its importance to California's marine fisheries, California spiny lobster (*Panulirus interruptus*) historically received little research within California waters (Mitchell et al., 1969; Pringle 1986; Barsky 2001) in comparison to other spiny lobster fisheries worldwide. Recently, however, increased effort has been applied to understanding California spiny lobster biology, ecology, and fisheries (Arteaga-Ríos et al., 2007; Mai and Hovel 2007; Parnell et al., 2007; Neilson and Buck 2008; Neilson et al., 2009; Koslow et al., 2012; Selkoe et al., 2010; Withy-Allen 2010; Miller et al., 2011a; Neilson 2011; Kay et al., 2012a; Kay et al., 2012b).

Table 1. Summary of existing (as of December 2012) California spiny lobster recreational and commercial fishing regulations in California.

Regulation	Fishery	
	Recreational	Commercial
Minimum Size	82.5 mm CL	
Seasonal Closure	Mid-March through September	
Permit Needed	Fishing License	Limited-Entry
Bag Limit	7 individuals	None
Capture Method	Diving by hand, Hoop Net	Trap
Catch Reporting	Report Card	Logbook
Mini-Season	5 days	NA

California spiny lobster (hereafter lobster) was commercially fished since the 1800s (Neilson 2011) with recreational or subsistence fishing likely as long. The commercial fishery peaked during the post-World War II years through the mid-1950s when the numbers of immature lobsters taken was recognized and accounted for in new regulations (Neilson 2011). Regulation changes between 1957 and 1976 reduced the catch of smaller, sublegal lobsters. Landings again increased in the late 1980s reaching a plateau of approximately 250 metric tons annually in the mid- to late-2000s (Neilson 2011; Koslow et al., 2012).

Recreational harvesting of marine species was long considered inconsequential in comparison to commercial landings, but recent evidence suggests otherwise (Eggleston et al., 2003; Coleman et al., 2004; Birkeland and Dayton 2005; Erisman et al., 2011). The southern California recreational lobster fishery landings over time are unknown and likely varied in response to lobster population abundances, angler participation rates, and advances in fishing technology. Minimal information on historic recreational catch and participation exists. The introduction of a lobster report card issued by the California Department of Fish and Wildlife (DFW) in 2008 may alleviate this problem in the future, but the lack of historic data hampers present analyses. This lack of information confounds understanding the population's health, in the absence of fishery-independent data, considering the recreational catch was estimated at 30–60% of the commercial catch (Neilson 2011).

The two lobster fisheries in California were governed by a suite of similar regulations but also fishery-specific rules (Table 1). Equipment used in each fishery bore relevance to this discussion. Traps were the only technology available to commercial fishers. Regulations governing their design remained unchanged since 1976. Market demand resulted in the commercial fishery targeting smaller individuals by utilizing smaller entrance funnels on each trap resulting in minimal variation in the harvested size since the 1980s (Neilson 2011; Barsky 2012; Healy 2012). In contrast, the recreational fishery targets all legal size classes, often prizing larger individuals (Neilson 2011). Recreational scuba divers once dominated the fishery with comparatively minor harvests by hoop net anglers (Neilson et al., 2009). This changed recently, coinciding with the introduction of a new rigid, conical hoop net (new hoop net) in 2006 (Tackletour 2006). More lobsters were landed per hoop net set using the new hoop net in comparison to the traditional hoop net (Neilson et al., 2009) thus raising concerns regarding their potential impact on the population if extensively adopted by the recreational fishery. Past experiences in other spiny lobster fisheries suggest this concern may be warranted. Recreational-only fishing periods used in Florida, similar to those used in California, resulted in significant

reductions in Caribbean spiny lobster (*Panulirus argus*) population density when pre-recreational season and pre-commercial season surveys were compared (Eggleston et al., 2003). Similar surveys have thus far not been completed in California.

To enhance management strategies, California resource managers recently completed a stock assessment despite limited fishery-independent population data (Neilson 2011) a noted shortcoming in the assessment (Cope et al., 2011). The lack of annual recruitment estimates and overall year class strength indices were highlighted as significant data gaps. Prior attempts to fill these gaps utilized historic plankton tows offshore off California (Pringle 1986; Koslow et al., 2012). Their results were informative of gross changes in population abundances, but inconclusive in explaining the interannual variation in lobster landings. Planktonic stage abundance indices often fail to predict future fishery patterns due to the variety of mortality sources acting on larval and pre-recruit stages (Houde 2008).

Coastal power plant marine life entrapment monitoring programs were found to provide previously unused data supporting fisheries analyses (Field et al., 2010; Erisman et al., 2011; Miller et al., 2011b; Miller and McGowan 2013). Invertebrate records were never evaluated, but hold promise as a fishery-independent data source. Furthermore, three monitored power plants were situated in the Santa Monica Bay, California where commercial lobster fishing was prohibited, but recreational fishing was permitted. Using these data, this work aims to investigate important concepts regarding the California spiny lobster population that directly affects the fishery's management. The primary purpose of this investigation is two-fold. First: fill knowledge gaps related to population abundance cycles over time; recruitment patterns and their relationship with the fishery landings; and interannual variability in larval settlement patterns. Second, use these complied data to test the hypothesis that the lobster population and commercial fishery have changed in measurable ways since the introduction of the new hoop net.

Material and Methods

Data Sources

Total annual commercial landings, in metric tons (MT), were compiled from Perry et al., (2010) for all DFW fishing blocks in southern California. Fishing blocks represented a designated spatial grid of 10-minute latitude × 10-minute longitude numbered areas, except along the coast where the coastline bounds the area and reduces the fishing block's overall size. Data was screened to remove those landings reported from fishing blocks encompassing bathymetry exceeding the lobster's known maximum depth (73 m; Barsky 2001) and accounted for < 1% of the total cumulative landings, 1980–2008. Spatial distribution of the total harvest (1980–2008 cumulative) was visualized using ArcGIS 10 with five natural breaks segregating the data.

Fishery-independent lobster data collected during power plant monitoring records as described by Miller and McGowan (2013) were compiled. Of the five power plants examined (Figure 1), three had intakes surrounded by soft-bottom sandy habitat where the intake structures themselves represented one of the few high-relief substrates in the area (Table 2). These were Scattergood Generating Station (SGS), El Segundo Generating Station (ESGS), and Huntington Beach Generating Station (HBGS). The primary Redondo Beach Generating Station (RBGS) intake was located near the King Harbor breakwall, a well documented mature artificial reef (Stephens et al., 1994). Lastly,
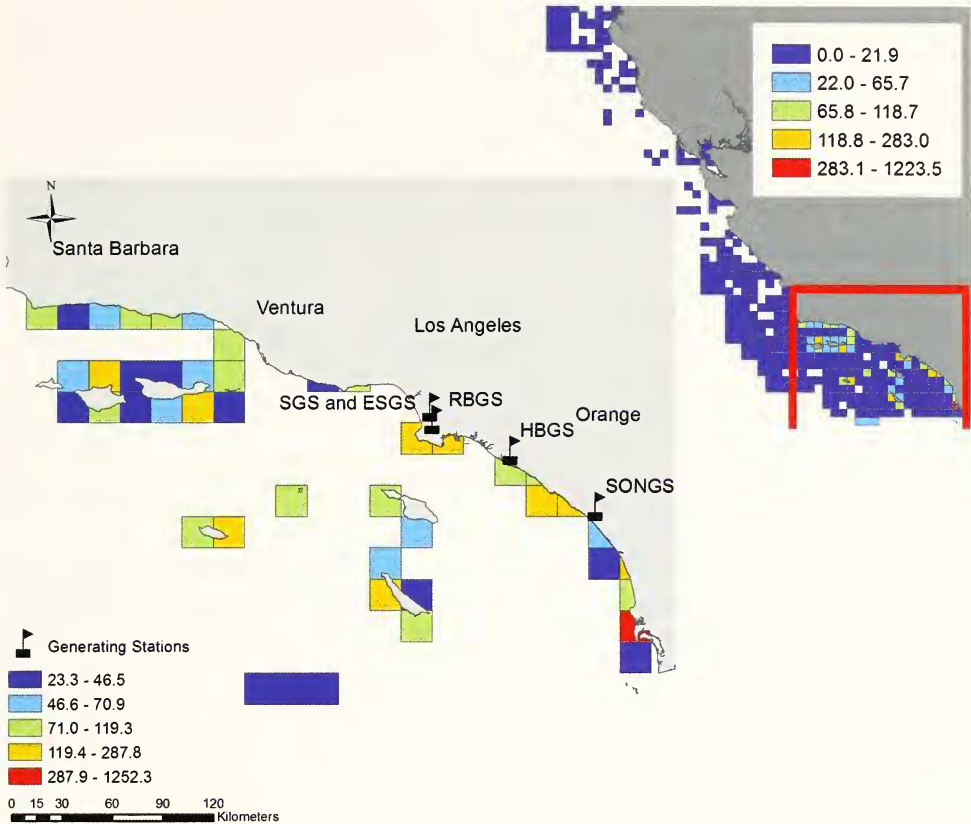
Fig. 1.   Total metric tons, based on landings, harvested from each California Department of Fish and Game fishing block, 1980–2008 commercial California spiny lobster seasons (October - March). The upper map depicts all Southern California Bight fishing blocks where lobster have reportedly been taken. The lower map depicts only those fishing blocks contributing > 1% of the total commercial landings, 1980–2008. Location of the four power plants used in this analysis is presented. They are San Onofre Nuclear Generating Station (SONGS), Huntington Beach Generating Station (HBGS), Redondo Beach Generating Station (RBGS), El Segundo Generating Station (ESGS), and Scattergood Generating Station (SGS). Scattergood and El Segundo are less than 3 km apart from each other with Scattergood upcoast from El Segundo.

San Onofre Nuclear Generating Station's (SONGS) intakes were situated adjacent to or in a cobble stone reef with a large kelp forest.

   At each power plant, the intake conduit emptied into a sedimentation basin (or forebay) within the power plant property. This reduces the overall water velocity and allows animals, such as fish and invertebrates, to take up residence within the forebay. Perpendicular to the conduit bulkhead lie steel mesh traveling screens designed to prevent large material from passing further into the cooling water system. Traveling screen mesh was 10-mm square mesh. At the discretion of power plant operators, a heat treatment was conducted to control biofouling growth within the cooling water system. This resulted in a forebay water temperature > 35°C for a minimum of one hour. During this time the traveling screens operated continuously removing all stressed and moribund marine life from the forebay. All material (marine life and debris) within the forebay became impinged upon the traveling screens, was carried out of the forebay, and washed off into

Table 2. Descriptive parameters for each power plant cooling water system monitored and supplying data on California spiny lobster abundance. Mean flow refers to the volume of cooling water circulated between heat treatments. Median carapace length (CL mm) and standard error for California spiny lobsters measured during surveys since 1993.

Parameter	Scattergood	El Segundo	Redondo Beach	Huntington Beach	San Onofre
# of Intakes	1	2	2	1	3
Intake Depth (m)	9.0	9.8	13.7	27.5	9.1
Riser Height (m)	3.2	3.0	3.0	2.4	2.9
Distance Offshore (m)	488	698	289	457	960
Habitat Surrounding Intake	Sand	Sand	Reef	Sand	Reef, Kelp
# of Surveys	100	208	277	192	272
Mean Flow (10^6 m^3) (SE)	273.8 (98.9)	66.1 (4.4)	87.6 (3.9)	59.7 (3.2)	168.5 (47.1)
Years Surveyed	1993–11	1980–10	1980–06	1980–98, 2001–10	1980–93, 2006–07
Median CL (mm)	76	79	72	13	66
Standard Error	0.45	0.81	0.35	0.97	1.35

a collection basket. At the end of the heat treatment, few, if any, animals remained within the forebay. Lobsters impinged during heat treatments were counted, batch-weighed, and measured to the nearest mm CL (beginning in 1993). The cooling water flow volumes between heat treatments were compiled from power plant records of daily cooling water circulated. Environmental data included the following indices: Pacific Decadal Oscillation (PDO; Mantua et al. 1997), North Pacific Gyre Oscillation (NPGO; Di Lorenzo et al. 2008), Multivariate ENSO Index (MEI; Wolter and Timilin 2012), and daily seawater temperature at 5 m (BST) recorded at the Scripps Institution of Oceanography (UCSD 2012).

Data Analysis

Fishing effort data was unavailable prior to 1997, therefore annual landings were presented unstandardized to effort. Both effort and landings data were provided by the DFW for the 2000–2010 fishing seasons (ca. October - March). Using these data, a catch per unit effort (CPUE; legal lobster count/trap pulled) was derived. Their use was limited due to the brevity of the CPUE series in comparison to the other data sets evaluated. The CPUE series was used to compare pre- and post-introduction of the new hoop net to investigate possible changes in the commercial fishery that could be attributed to the new recreational fishing technology. Comparisons were made using a Kruskall-Wallis test.

Lobster abundance and biomass data collected during power plant monitoring were standardized to circulated cooling water volumes to account for variation between plants and daily operations over time. The resulting entrapment rate (ER; count/10^6 m^3) was used in subsequent analyses. Trends were tested for significance (meaningfulness) using a MS Excel add-in wherein the lobster time series was broken into intervals of varying length before analyzed using linear regression (Bryhn and Dimberg 2011). Individual weights were not recorded during surveys; therefore a mean individual weight was derived by dividing the aggregate biomass by the total count. This supplemented the size information collected after 1992. Median carapace lengths were calculated for lobsters measured at each power plant to indicate the size structure sampled. The annual median length (total, female, and male) from lobsters collected at SGS was examined for changes in the overall size structure with time at a location free of commercial fishing pressure.

Sampling dates were matched to years corresponding to the fishing seasons and intervening period before the next season, i.e. October 1 - September 30. For example, data collected from October 1, 2009 - September 30, 2010 was included in the 2009 annual median length. This analysis was limited to SGS as it was the only power plant meeting two criteria: 1) located in the Santa Monica Bay where commercial fishing was disallowed, 2) robust sample size in years before and after the new hoop net introduction. The remaining power plants did not meet both of these criteria (Table 2). A Kolmogorov-Smirnov test was used to compare lengths from the two periods, pre- and post-new hoop net.

Individuals between 72.5 and 81.5 mm CL were assumed to represent new fishery recruits the following year. Their abundance by heat treatment was standardized consistent with the ER technique to derive the next-year's-fishery-index (NYFI; count/10^9 m^3). Assuming commercial landings predominantly represent first-year recruits (Neilson 2011), landings were plotted as a function of the NYFI after advancing the index one year. Individuals measuring less than 21 mm CL were assumed to be young-of-the-year. From their survey-specific abundance, a young-of-the-year index (YOYI, count/10^9 m^3) was derived following the same methods described for the ER and NYFI. Environmental indices were compared with the YOYI to examine the potential relationship between the environment, as measured by the indices, and lobster settlement using a Spearman's rank correlation. When identified, autocorrelation was addressed by adjusting the r_{crit} using the modified Chelton method (Pyper and Peterman 1998). All statistical analyses, other than the power plant trend analysis, were completed in R (R Development Core Team 2012).

Results

California Department of Fish and Wildlife records indicate lobster has been taken commercially across a wide portion of the California coastline (Figure 1). The majority of fishing blocks contributed less than 22 MT of landed lobster during the 29 years reviewed. These areas were excluded and the remaining analyses focused on the 43 fishing blocks supporting the bulk of the commercial fishery. Landings from the southern portion of the area were generally higher than those farther north (Figures 1 and 2a), including the peak along Point Loma in San Diego, California. Additional areas producing high biomass landings included rocky headlands at Dana Point and Palos Verdes along the mainland, and at San Clemente, San Nicholas, Santa Cruz, and Santa Rosa Islands.

A shift in the early 1990s indicated increased landings from areas outside of San Diego County (fishing block series 800). The mean seasonal percentage of the total landings prior to 1994 in the southernmost fishing blocks accounted for 55% but declined to 45%, on average, through 2008 (Figure 2b). During this 1994–2008 period, landings in the 700-series fishing blocks offshore of Los Angeles and Orange Counties increased by only 2%, on average, from their 1980–1993 mean. Landings from the 600-series fishing blocks offshore of Santa Barbara and Ventura Counties increased 8% during the latter 15 years in comparison to the 1980–1993 period.

Commercial landings from these 43 blocks initially declined to a minimal level (<150 MT/annually) in the 1980s before increasing to relatively consistent annual landings of approximately 250 MT since 2000 (Figure 3a). Since 2000, the mean annual CPUE has remained > 0.36 legal lobsters/trap and ranged as high 0.54 legal lobsters/trap (Figure 3b). Prior to the introduction of the new hoop nets in the recreational fishery,
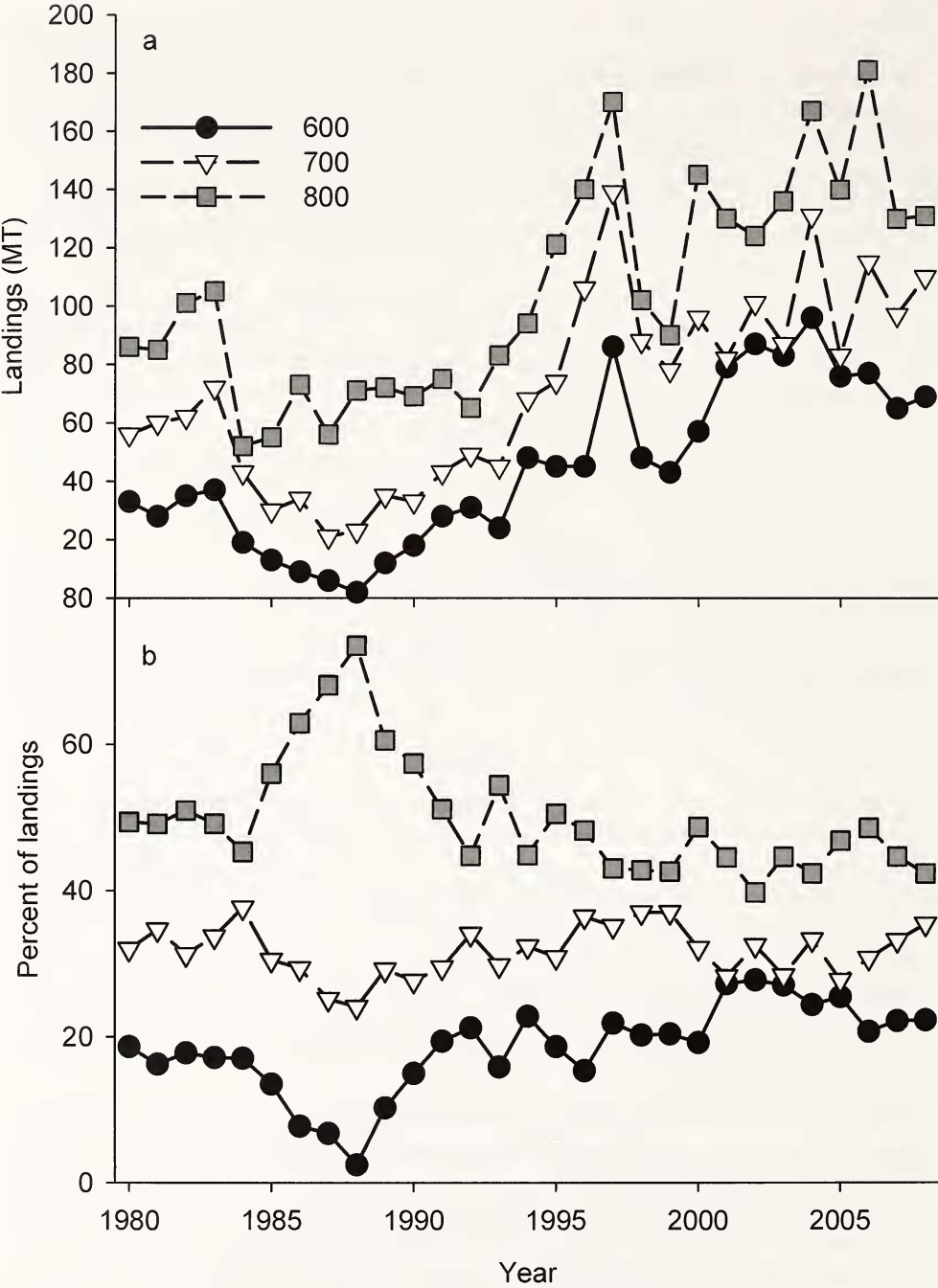
Fig. 2.   a) Total California spiny lobster landings (metric tons, MT) by fishing block series and fishing season; b) percent of landings by fishing block series. Block series: 600 = Santa Barbara and Ventura Counties, California; 700 = Los Angeles and Orange Counties; 800 = San Diego County.
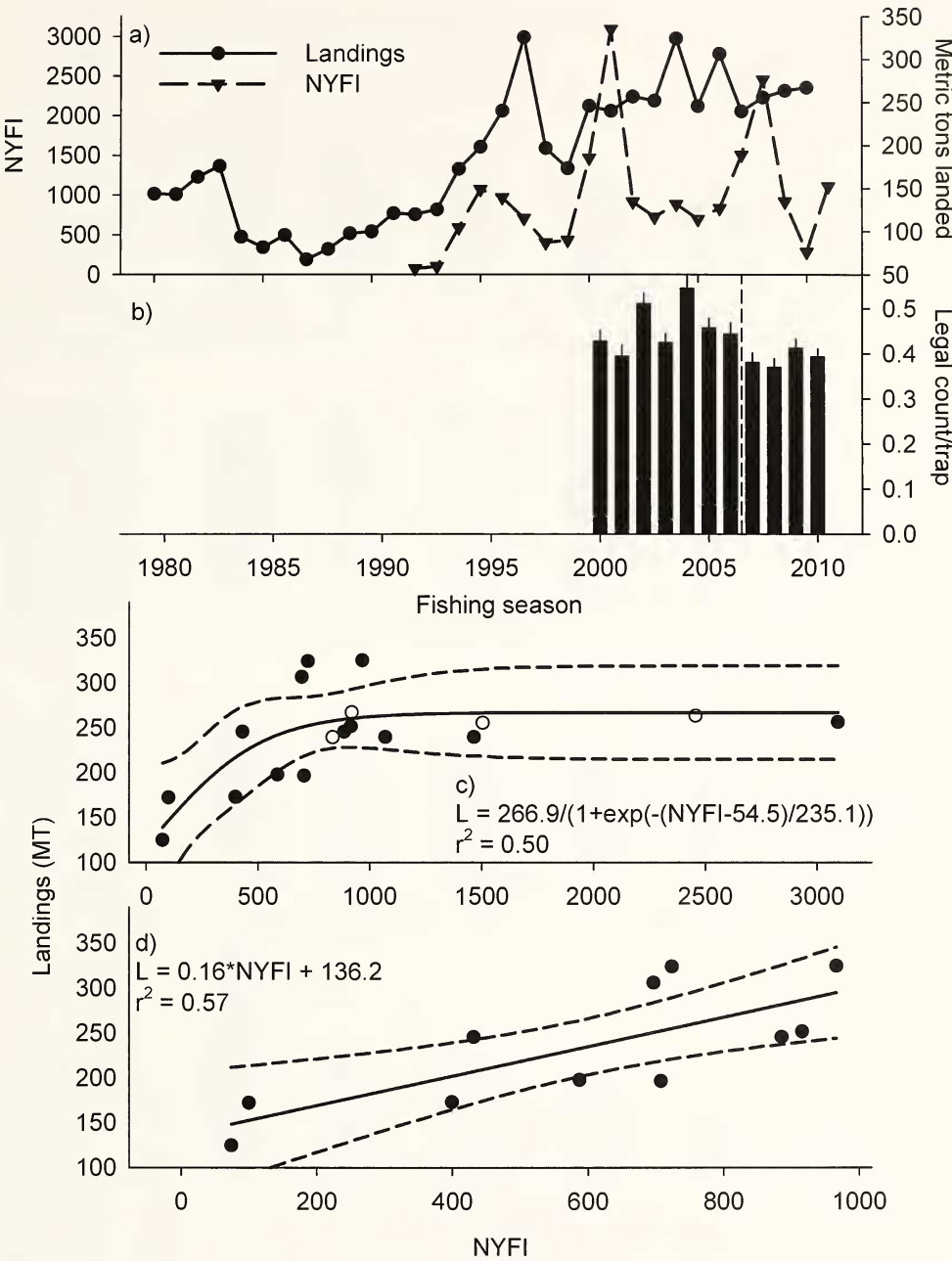
Fig. 3. a) Commercial California spiny lobster landings from those fishing blocks contributing $\geq 1\%$ of the total commercial landings, 1980–2008. The next-year's-fishery-index (NYFI; count/10^9 m^3) by year derived from power plant entrapment surveys (1992–2011). b) Commercial fishery catch per unit effort (legal count/trap pulled) for the same fishing blocks used for a). c) Total landings (1993–2010) plotted as a function of the NYFI after adjusting for a one-year lag. White circles indicate those seasons since the introduction of a rigid-style hoop net in the recreational fishery (2007–2010). A sigmoidal function best described the distribution ($r^2 = 0.50$). Dashed lines indicate 95% confidence intervals. d) Subsampling data from figure 3c for just NYFI $< 1000/10^9$ m^3, or the asymptote threshold indicated in figure 3c resulted in greater predictability ($r^2 = 0.57$). Dashed lines indicate 95% confidence intervals.

the commercial CPUE averaged 0.46 legal lobster/trap. After the 2006 introduction, this declined to 0.39 legal lobster/trap, or a significant 15% reduction (KW, $\chi = 3.98$, df = 1, p = 0.046). Interannual CPUE variability declined after the 2006 season as the coefficient of variation declined from 1.00 prior to 2007 to 0.89 after 2006. Changes in the CPUE at the onset of this introduction were prominent across the Southern California Bight with mean monthly CPUE across all block series lower after the introduction, with one exception (Figure 4). The disparity between the two periods was generally higher during the first one-half of the season in all areas (Figure 4 b–d). In the San Diego area (fishing blocks numbered 801-899), the disparity was greatest during the first three months and waned thereafter, with post-introduction February CPUE slightly exceeding the pre-introduction mean. This was the only instance of the post-introduction period exceeding the pre-introduction mean.

Trends in the fishery-independent population indices at each power plant were independent of each other with some exceptions (Figure 5). Entrapment rate trends at SGS significantly correlated with both ESGS (r = 0.58, p = 0.01, n = 18) and HBGS (r = 0.63, p < 0.01, n = 17). No correlation existed between the ESGS and HBGS trends. Trends at RBGS and SONGS were not correlated with any other power plant. Where data were available, an overall increasing trend in lobster population abundance (higher ER) was recorded beginning in the late-1980s, (Figure 5a). Monthly ER averaged over the entire series indicated general peak abundance in late-summer to early-fall period at each power plant (Figure 6). The ER at RBGS was the lone exception as it peaked in spring.

Three power plants in Santa Monica Bay recorded data from an area free from commercial fishing pressure. At SGS, the farthest north of the three Santa Monica Bay power plants, lobster data was available beginning in 1993, from which a meaningful increase in ER was observed though 2011 ($r^2 = 0.51$, p < 0.001), excluding a brief depression in 2005 (Figure 5b). The SGS data were dominated by lobsters near the legal size limit (Table 1). Length measurements recorded at SGS were available from every year, 1998–2011. This was the only Santa Monica Bay power plant length series sufficiently spanning 2006 when the new hoop nets were introduced. Lobster carapace lengths pre-introduction were significantly larger than post-introduction across all samples (KS, D = 0.0998, p < 0.001; Figure 7a) and for females (KS, D = 0.1323, p < 0.001; Figure 7b), but not for males (KS, D = 0.0705, p = 0.10; Figure 7b). At nearby ESGS, the ER was more variable than at SGS and extended to 1980 (Figure 5c). Lacking any significant trend, generally higher ERs were observed at ESGS in the last decade than during the preceding two. Most lobsters taken at ESGS were also near the fishery's minimum size with the largest median CL recorded. Average weight of lobsters taken at ESGS was more variable prior to 1993, with a fairly stable mean weight of 500g during the 1993–2008 period before declining in later years. At the southeast edge of the Santa Monica Bay, RBGS also commonly entrapped lobsters with no significant trend detected, but declining cooling water use by RBGS reduced the need for heat treatments (Figure 5d). Therefore, the usable time series ended in 2006. Entrapment rates at RBGS were also predominantly reflective of lobsters near recruiting to the fishery. Mean biomass of lobsters entrapped prior to 1990 were 80 g larger than after, suggesting an increased influence of smaller individuals since 1990.

Huntington Beach Generating Station entraps few lobsters in comparison to the Santa Monica Bay power plants, and as with prior examples, a statistically insignificant abundance trend was observed (Figure 5e). In 1989, and several years after, the ER
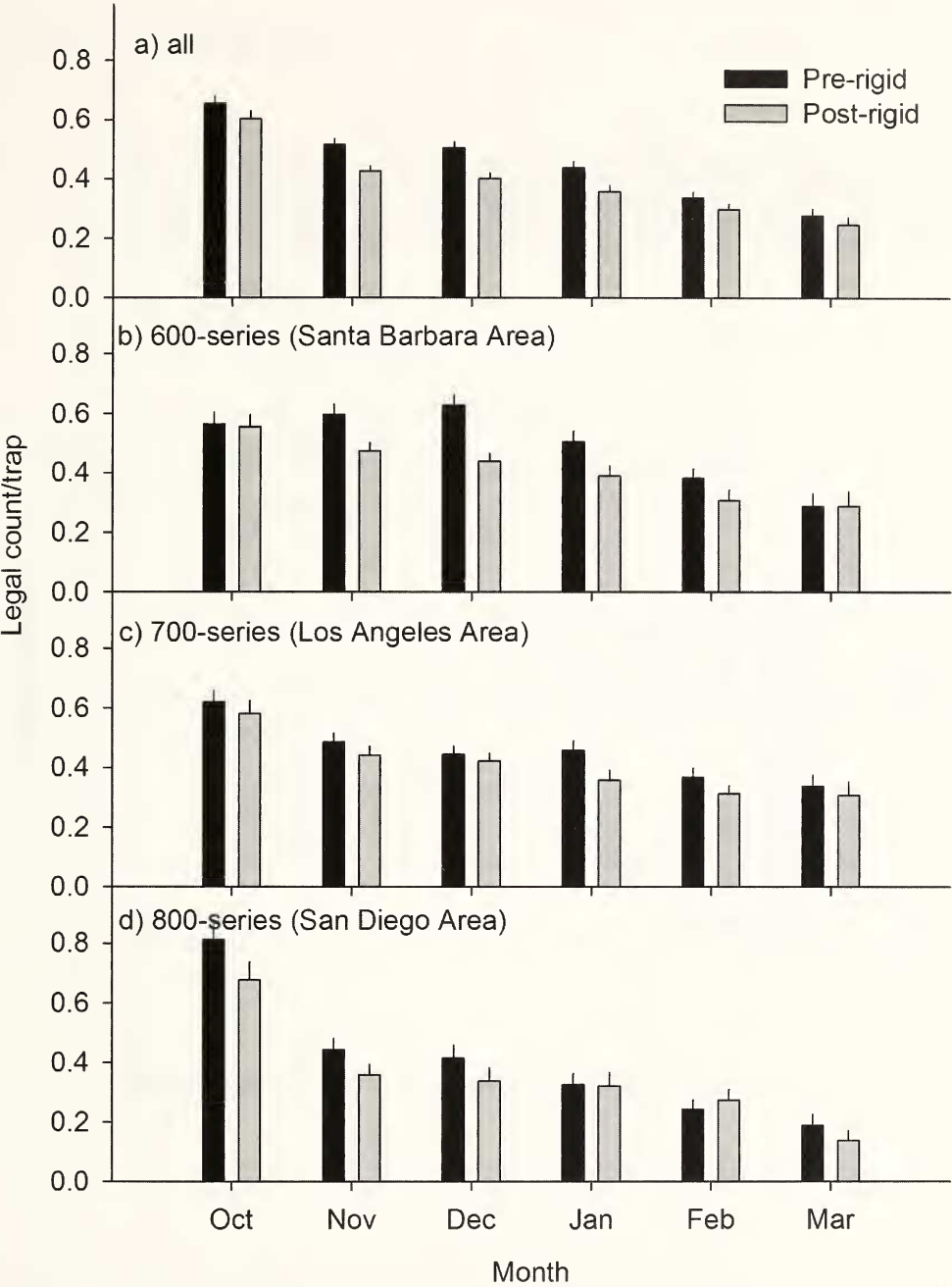
Fig. 4. Mean monthly commercial California spiny lobster catch per unit effort (± s.e.) before (2000–2006) and after (2007–2010) the introduction of the rigid-style hoop net for recreational fishers a) across all fishing blocks in the 600–800 series, b) 600-series blocks, c) 700-series blocks, d) 800-series blocks.

periodically increased substantially as a comparatively large number of lobsters were taken. Excluding 1989, the mean HBGS ER after 1989 was nearly four times greater than was recorded prior to 1989. Unlike the three Santa Monica Bay power plants, lobsters taken at HBGS were considerably smaller with a median CL of 13 mm (Table 2). This
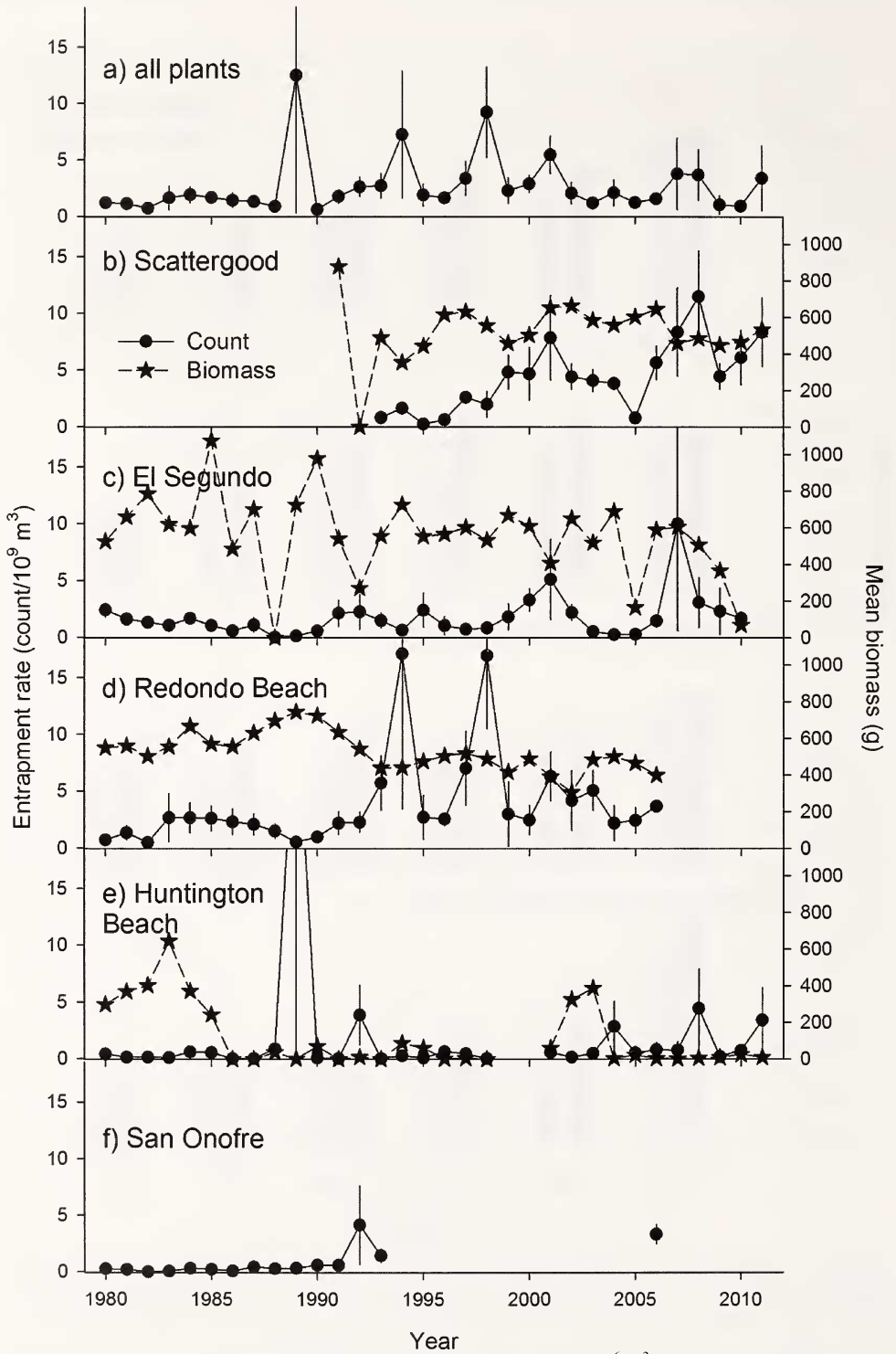
Fig. 5.   Mean annual California spiny lobster entrapment rate (count/10⁶ m³) at a) all plants combined, b) Scattergood (1993–2011), c) El Segundo (1980–2010), d) Redondo Beach (1980–2006), e) Huntington Beach (1980–1998, 2001–2011), and f) San Onofre (1980–1993, 2006). Mean biomass (g) per individual lobster for b, c, d, and e by year derived from total abundance/total biomass, not individual weights. Therefore, no measure of variation around the mean.
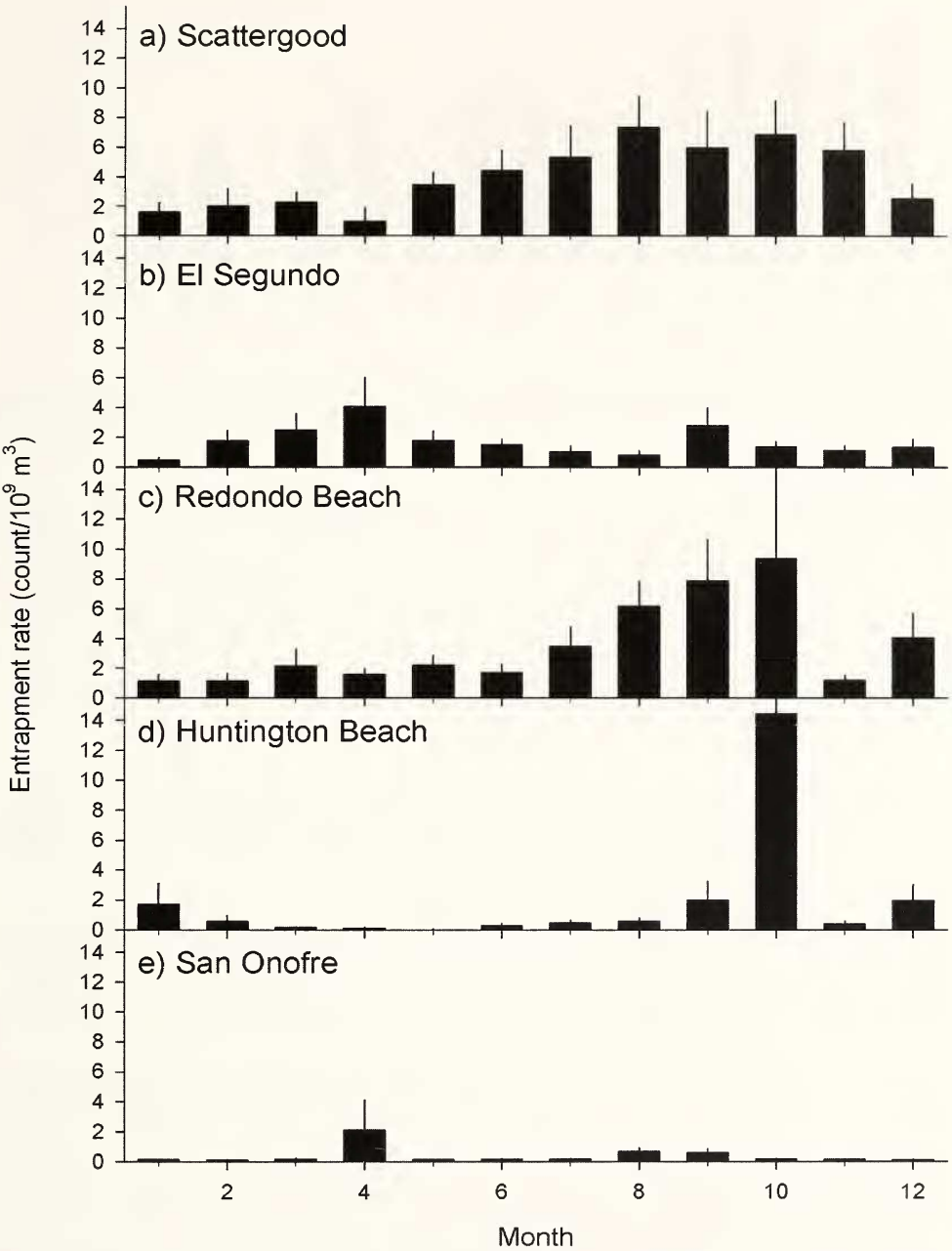
Fig. 6. Mean monthly California spiny lobster entrapment rate (count/10^6 m^3) at each of the five power plants: a) Scattergood (1993–2011), b) El Segundo (1980–2010), c) Redondo Beach (1980–2006), d) Huntington Beach (1980–1998, 2001–2011), and e) San Onofre (1980–1993, 2006).

small CL was consistent with the trends in biomass and the sporadic high ERs recorded. Prior to 1989, the mean lobster weighed 388 g but declined after 1988 to 9 g. In 1989, the most abundant year at HBGS, the mean individual biomass was 1 g.

Comparatively minimal data was available from SONGS, but those data indicated a consistently low ER through 1991 before increasing in 1992 to 4 lobster/10^9 m^3 and
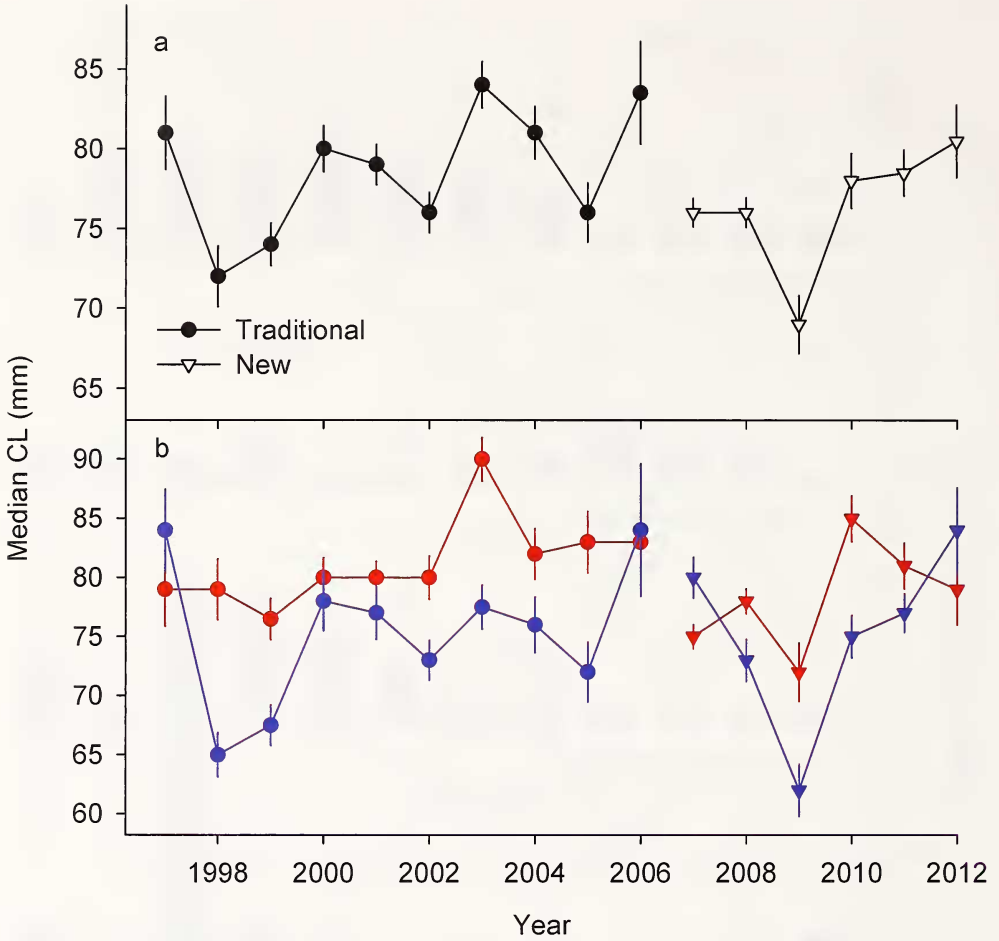
Fig. 7. Median (±s.e.) California spiny lobster carapace length (mm) of lobsters taken during power plant surveys at Scattergood (1998–2012) divided by periods where the traditional hoop net (Traditional) and new hoop net (New) were used for all lobsters a) combined and b) by sex (female in red, male in blue). Data was adjusted to correspond to California spiny lobster fishing seasons, October 1 - September 30. For example, October 1, 2009 - September 30, 2010 = 2009.

remaining above 1 lobster/10^9 m^3 in 1993 when lobster entrapment monitoring stopped (Figure 5f). A special study in 2006 recorded 3 lobster/10^9 m^3, consistent with the remaining plants in a higher ER recorded recently in comparison to annual mean ERs prior to 1989. The median CL for lobsters collected at SONGS was 66 mm or similar to all other sites except HBGS (Table 2).

The annual NYFI trend was insignificant, but several well-above average recruitment events occurred since 1993 (Figure 3a). Large recruitment events in 2001 and 2008 were especially noteworthy as they stood out considerably from the remaining years. This corresponded to the period of increasing and stable commercial landings. The commercial landings were successfully predicted by the NYFI in a sigmoidal regression: Landings = 266.9/(1+exp(-(NYFI-54.5)/235.1)) (r^2 = 0.50, p = 0.02; Figure 3c). The sigmoidal curve reached an asymptote at an NYFI = 1000/10^9 m^3 as commercial landings were consistently between 250 and 265 MT in years with an NYFI > 1000/10^9 m^3. Therefore the NYFI was subsampled to include only years with < 1000/10^9 m^3
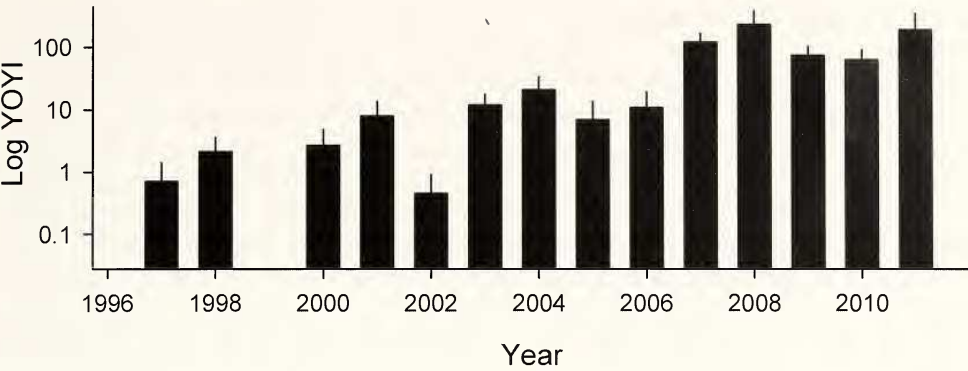
Fig. 8.   The mean annual (1993–2011) California spiny lobster young-of-the-year index (YOYI) plotted on a log scale. Data drawn from surveys at Scattergood, El Segundo, Redondo Beach, and Huntington Beach.

(Figure 3d). Greater landings predictability was achieved ($r^2 = 0.57$, $p < 0.001$) using the linear relationship L = 0.16*NYFI + 136.2. Derived through similar methods as the NYFI, beginning in 1992 when measurements started, the YOYI indicated minimal larval settlement until 1997 (Figure 8). Since 1997, young-of-the-year lobsters were entrapped every year with the exception of 1999. When adjusted for autocorrelation in both the YOYI and NPGO, no significant correlation was detected with any of the environmental indices (Table 3).

Discussion

  Spiny lobsters are prized marine species targeted chiefly by commercial fishing interests throughout their global range (Phillips 2006). In many cases, the local spiny lobster fishery ranks among the most valuable fisheries in the area due to the high price per kg. This value leads to extensive interest in achieving a sustainable fishery, often through intensive monitoring and fishery investigations (Pringle 1986; Cruz et al., 1995; Acosta et al., 1997; Cruz and Adriano 2001; Eggleston et al., 2003; Phillips et al., 2005; Phillips and Melville-Smith 2005; Arteaga-Ríos et al., 2007; Parnell et al., 2007; Neilson et al., 2009; Phillips et al., 2010; Miller et al., 2011a; Kay et al., 2012b). Despite its prominence in California's commercial fisheries (Mitchell et al., 1969; Barsky 2001), few studies examined the lobster population and fishery in California to adequately inform management. The need for fishery-independent population data, especially for pre-recruit age

Table 3.   Spearman rank correlation results for tests between California spiny lobster young-of-the-year index and each climate/oceanographic index. Indices tested include North Pacific Gyre Oscillation (NPGO), Coastal Upwelling Index (CUI), Pacific Decadal Oscillation (PDO), Multivariate ENSO Index (MEI), and bottom sea temperature (BST). Autocorrelation test results using a Durbin-Watson test (DW) are presented in addition to the r_{crit} derived in cases where autocorrelation were detected in either the climate/oceanographic or lobster abundance index.

Index	DW	DW p	r	p	r_{crit}
NPGO	0.58	<0.01	0.49	0.03	0.79
CUI	1.79	0.21	0.02	0.94	0.68
PDO	1.44	0.03	−0.48	0.03	0.68
MEI	1.67	0.13	−0.33	0.15	0.68
BST	1.47	0.04	−0.27	0.24	0.68

and size classes, was recently outlined (Cope et al., 2011). Without such data, fishery managers were forced to rely on landings information and other fishery-dependent data, which can lead to a misrepresentation of the population status (Erisman et al., 2011).

Seeing these gaps, a review of both fishery data and a novel power plant time series was executed to try and gain a greater understanding of the populations. Several points, discussed in greater detail below, became apparent. These included: 1) landings steadily increased in recent decades, but the associated effort was undocumented; 2) regulatory concerns over the new hoop net design were likely warranted; 3) timing of the 1980s increase in the lobster population and subsequent landings coincided with the 1989 oceanographic regime shift; and 4) no evidence was found linking the recent increase in southern California lobster landings to currently-available and commonly used climate indices.

Commercial fishing harvested lobsters from throughout the Southern California Bight, but the majority of the landings were reportedly taken from fishing blocks offshore Los Angeles County and south. Along the mainland coast, prominent rocky headlands such as Palos Verdes in Los Angeles County, Dana Point in Orange County, and Point Loma in San Diego County contributed the majority of lobster landings over time although the fishery expanded north in later years. These patterns may be artifacts of effort distribution. In the absence of effort data, this cannot be ruled out. It stands to reason, however, that areas where lobsters have been caught before were likely targeted again.

Notable areas without any reported commercial landings include the leeward side of Santa Catalina Island and within the Santa Monica Bay, both areas where commercial lobster fishing was prohibited. During the 2010–11 season, the third through fifth highest ranked sites for recreational lobster catch (35,356 lobsters reportedly caught) were within or near Santa Monica Bay (California Department of Fish and Wildlife 2012). Santa Catalina Island ranked first, although no information on location was included to place the catches in or out of areas closed to commercial fishing. Fishery-independent data was robust in the Santa Monica Bay due to the presence of three monitored power plants. Each recorded stable to increasing abundance indices, although two of the series terminated prematurely due to vagaries in the electricity generation industry.

The third Santa Monica Bay power plant, SGS, provided robust data during most of the population rise and recorded the only meaningful positive trend in abundance. Lobsters collected at SGS were near the minimum size for the fishery, but a significant decrease in the lobster size structure was observed between 2006 and 2007. The significant difference between the pre-2007 and post-2006 periods was represented in the combined sample across both sexes and for females; no significant difference was detected in males. Spiny lobsters execute seasonal movements, typically onshore offshore timed with changes in water temperature (Mitchell et al., 1969; Kanciruk and Herrnkind 1978), but no longshore migration has thus far been reported for lobsters after settling from the plankton. The lack of robust size and catch information from the recreational fishery precluded any clear conclusions, but the reduction in size in an area free of commercial fishing pressure was cause for concern. This was especially disconcerting given the significant change in females. Increasing evidence suggests losses of bigger and older females severely impacts fisheries well beyond losses of smaller, younger females due to the exponentially higher fecundity and genetic makeup associated with attaining old age and large size (Berkeley et al., 2004a; Berkeley et al., 2004b; Birkeland and Dayton 2005). Furthermore, the timing of the downsizing lends more circumstantial evidence suggesting an effect of the new hoop net. More data is needed to verify this impact, but the present

data should elicit cautionary management practices to protect the resource while additional data is acquired.

Regardless of the spatial distribution in catch, sustained, elevated landings throughout the 2000s were assumed to reflect a sustainable fishery (Neilson 2011). These patterns, however, belie potential pitfalls in the future related to variable fishing effort (and efficiency) and environmental forcing. While insufficient data existed to conclusively determine an impact, the introduction of the new hoop net and its increasing use (Neilson and Buck 2008) appeared to impact the commercial fishery and population at large. This was consistent with comments of commercial fishers, who claimed to catch fewer lobsters with more effort (Neilson 2011). In itself, a redistribution of harvest between the recreational and commercial interests may not be cause for alarm. It does, however, indicate that the recreational harvest may be substantial and warrants careful consideration in management actions. The declining size collected at SGS should be cause for alarm and investigation. Unfortunately, insufficient data exists on the scope of the recreational fishery, especially core parameters such as the number of active participants and some measure of their annual catch and size structure to support a clear conclusion on this matter. Examination of the recreational harvest effects during a recreational-only mini season in Florida for *Panulirus argus*, similar to the mini season for California spiny lobster in California, indicated substantial reductions in the local, legal-sized population prior to the opening of the commercial fishery (Eggleston et al., 2003).

Like many fish species, lobster abundances and fishery were robust when strong larval settlement and subsequent recruitment occurs (Beaugrand et al., 2003; Beaugrand and Kirby 2010), such as the latter period for lobster in southern California. Harvest pressure from commercial and recreational interests during periods of declining settlement can quickly lead to overfishing, e.g. *Gadus morhua* (Beaugrand et al., 2003; Beaugrand and Kirby 2010). Such was the case in the Hawaiian spiny lobster fishery in the Northwest Hawaiian Islands where recruitment declined 47% after 1989 without an accompanying decline in fishing effort eventually leading to a fishery collapse (Polovina et al., 1995; Polovina 2005). While lacking any statistical link between the climate indices tested and either population or fishery abundance indices, the timing of changes in California's spiny lobster populations were highly coincidental with the documented 1989 regime shift. The 1989 regime shift resulted in substantial changes to the Southern California Bight coastal fish populations with a similar lack of correlation with common climate indices (Miller and McGowan 2013). Polovina (2005) hypothesized the shift altered current patterns in the waters surrounding the Hawaiian Archipelago resulting in decreased productivity and, perhaps more importantly, disrupted larval dispersal and delivery patterns. Both the California and Hawaiian spiny lobsters pass through a lengthy larval phase with their larval drift predicated on local currents. Growing genetic evidence suggested changes in long-held beliefs of larval supply to southern California from Baja California was warranted, such that the local populations may be self-supporting (Selkoe et al., 2006; Selkoe et al., 2007; Selkoe et al., 2010; Iacchei et al. 2013). Given the 1989 shift appeared to be a Pacific-basin wide phenomena, a similar shift in current patterns within the Southern California Bight likely occurred to the benefit of the local lobster population.

Perhaps the strongest indication of a positive shift in lobster settlement in the late-1980s was recorded in the power plant monitoring. This was especially true at HBGS where after two years of no lobsters recorded (1987–88), the highest ER occurred in 1989. Unlike previous years, the average lobster weighed approximately 1 g (695 lobsters

weighing 777 g). In 16 of the following 19 years of monitoring (no surveys in 1999–2000) where the ER was ≥ 1, the average lobster weighed less than 10 g 50% of the time. A similar, albeit less demonstrative, shift towards smaller individuals was recorded at the remaining power plants. The location of the HBGS intake likely made it an effective puerulus/juvenile lobster collector. Situated offshore of sandy beaches along an extensive stretch of soft-bottom habitat, the HBGS intake structure and surrounding riprap represented one of the few suitable habitats in the immediate area for puerulus to settle out of the plankton. Abundances of settling *Jasus verreauxi* in collectors placed over sandy bottom habitat offshore from natural habitat known to attract settlers was significantly higher than those placed near preferred natural habitats (Montgomery 2000). While both SGS and ESGS were both located in similar habitat, neither recorded the level of larval settlement observed at HBGS. Lacking additional information, no hypothesis can be presented for this difference at this time. Nevertheless, this warrants further investigation incorporating time series data on current patterns and productivity in the Southern California Bight, similar to that completed for the Hawaiian Archipelago (Polovina et al. 1993; Polovina et al. 2005).

This apparent pattern of increasing settlement likely led to the continually high landings in the commercial fishery over the last decade. The increasing strength of the YOYI suggests the population will continue to support a robust harvest in the near term. Deriving a maximum sustainable yield for the combined fisheries (commercial and recreational), however, remains an unsettled matter. Given the size classes targeted by each fishery, the commercial landings will likely decline earlier than the recreational fishery. Designing traps to preferentially target new recruits minimizes the impact of taking larger, more fecund females. This practice has more potential to result in a sustainable fishery in comparison to those that target larger, trophy individuals (Berkeley et al., 2004a; Berkeley et al., 2004b; Birkeland and Dayton 2005). Reliance on one or two recently-recruited year classes, however, renders the commercial fishery more susceptible to recruitment failure than the recreational fishery. Fishing equipment available to the recreational fishery does not suffer such size selectivity.

Conclusion

The fisheries were clearly landing high biomass (in comparison to the 1980s) as recently as 2010, the last year of fishery data included in this study. Reasons for concern were present that warranted further investigation. Specifically, the introduction and use of a new hoop net in the recreational fishery raised concern. While the commercial fishery was extensively regulated as a limited entry fishery supplying catch statistics each calendar year, the recreational fishery required only a fishing license with, until 2008, no requirement to report catch statistics. Prior attempts to examine the lobster population and fisheries were impacted by the limited availability of fishery-independent data. Utilizing novel data collected at local power plants assisted with this evaluation. These data suggested the lobster population was more robust in recent decades than during the 1980s due to increased larval settlement. Mean lobster weight indicated increased larval settlement in the area beginning in 1989, coincidental with the timing of an oceanographic regime shift to one promoting lobster settlement in southern California. These data and analyses all indicate that while the lobster fishery in southern California appears healthy at the moment, it warrants careful management in the face of variable ocean conditions. Most pressing was the need to better monitor and document the recreational fishery and monitor sublegal size classes from larval settlement through fishery recruitment.

Acknowledgements

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